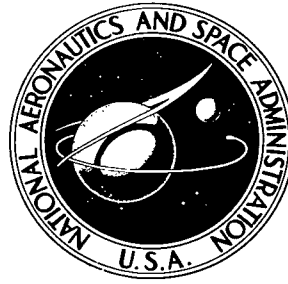


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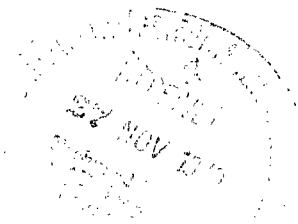


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# ZERO-GRAVITY EQUILIBRIUM CONFIGURATION OF LIQUID-VAPOR INTERFACE IN TOROIDAL TANKS

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16. Abstract The configuration of the liquid-vapor interface for a wetting liquid in a toroidal tank during weightlessness is observed for a range of percent liquid volumes, tank sizes, and initial conditions. Results are presented in photographic and chart form and compared with previous data. The final liquid-vapor interface configuration is shown to be dependent on tank mounting angle, percentage of liquid volume, and tank proportion.					
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# **ZERO-GRAVITY EQUILIBRIUM CONFIGURATION OF LIQUID- VAPOR INTERFACE IN TOROIDAL TANKS**

**by Eugene P. Symons**  
**Lewis Research Center**

## **SUMMARY**

An experimental investigation was conducted in a weightless environment to study the configuration of the liquid-vapor interface in toroidal tanks for a  $0^{\circ}$ -static-contact-angle liquid. Results are presented for a range of liquid- to tank-volume percentages for tanks initially positioned both horizontally and at angles to the gravity field prior to the test. This effectively varied the initial condition of the interface before entering weightlessness. The results indicate that there are two interface configurations, depending on tank mounting angle, percentage of liquid volume, and tank proportion. At low percentages of liquid volume, the liquid positioned itself on the tank wall area furthest from the tank axis. For moderate to high percentages of liquid volume, the liquid completely filled one or more segments of the tank.

## **INTRODUCTION**

Experimental investigations of the configuration of the liquid-vapor interface in various tank geometries during weightlessness have been the basis for many experimental programs conducted in the Lewis Research Center's drop towers. The geometries considered in these investigations generally were restricted to cylinders and spheres (refs. 1 to 4) because of their applicability to present-day spacecraft. Recently, however, other tank geometries such as spheroids, cones, and toroids have been suggested for use, primarily because of efficient vehicle packaging. A basic requirement for evaluation of each of the suggested tank geometries is a knowledge of the configuration of the liquid-vapor interface during weightlessness so that operations such as liquid expulsion and venting of excess tank pressure can be accomplished efficiently.

In a previous study (ref. 5), this author conducted an investigation of the liquid-vapor interface configuration in toroids. In that work, two basic zero-gravity interface

configurations were observed and were found to depend on the percentage of liquid volume in the tank and the initial angle of inclination of the tank prior to entering weightlessness. However, at intermediate percentages of liquid volume with the tank initially positioned horizontally, no final configurations were observed due to the limited test time available (2.2 sec). This region was termed a transition region, since at the conclusion of the test the liquid-vapor interface was apparently in a transition between the normal-gravity and the zero-gravity equilibrium configurations.

The purpose of this report is to examine this transition region over a longer period of time in order to more accurately define the final equilibrium zero-gravity configuration and to extend the data obtained in the earlier work to tanks of larger size. Results are presented for a range of percent liquid volumes in tanks positioned both horizontally and at various angles to the gravity field prior to the weightless test. The angle tests simulate the effect that nonaxial accelerations might have on positioning the liquid-vapor interface away from its normal position in the actual tank before entering weightlessness. For completeness, results include some of the data taken from the previous work (ref. 5).

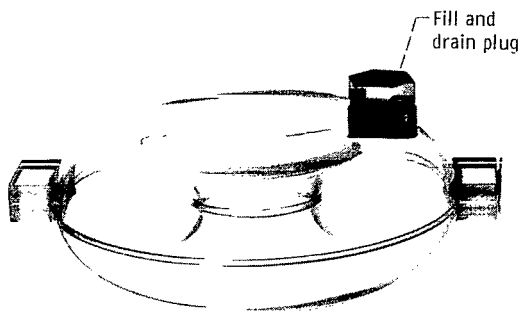
## APPARATUS AND PROCEDURE

A description of the experiment vehicle and the facility employed in this study together with their operating procedure can be found in the appendix.

### Experiment Tanks and Test Liquid

Experiment tanks used for this study were toroids machined from cast acrylic plastic and polished for optical clarity. Four tank sizes were tested with major radii  $R$  of 8, 4, 3, and 2 centimeters and with respective minor radii of 4, 2, 1, and 1 centimeters (see fig. 1). The tank size was limited by the space available in the experiment package and by the total free-fall time of 5.16 seconds.

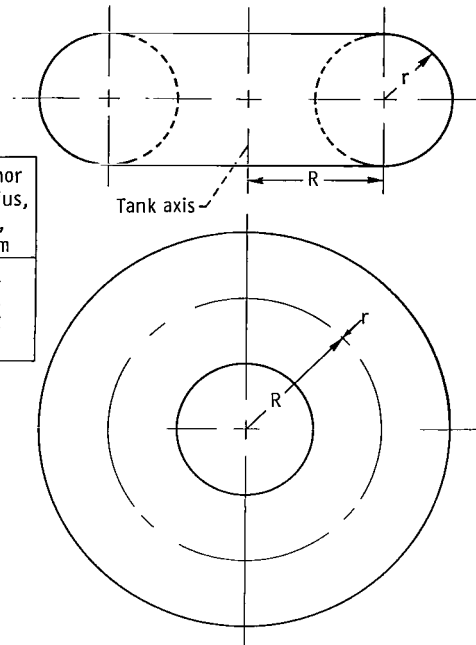
The only test liquid used was anhydrous ethanol. This particular liquid was chosen since it exhibits an essentially  $0^\circ$  static contact angle on cast acrylic plastic and thus duplicates the static contact angle of most propellants on spacecraft tank materials. A small amount of dye was added to the test liquid. The addition of this dye had no measurable effect on the fluid properties.



C-67-2126

(a) Typical toroidal test tank.

Major radius, $R$ , cm	Minor radius, $r$ , cm
2	1
3	1
4	2
8	4



(b) Toroidal tank dimensions.

Figure 1. - Experiment tanks.

## Tank Mounting Angle

In order to determine the effect of initial conditions on the final equilibrium liquid-vapor interface configuration, the toroid was initially mounted at some angle to the gravity field prior to entering weightlessness (see fig. 2). This angle of inclination is termed the tank mounting angle  $\theta$  and was a variable in this study.

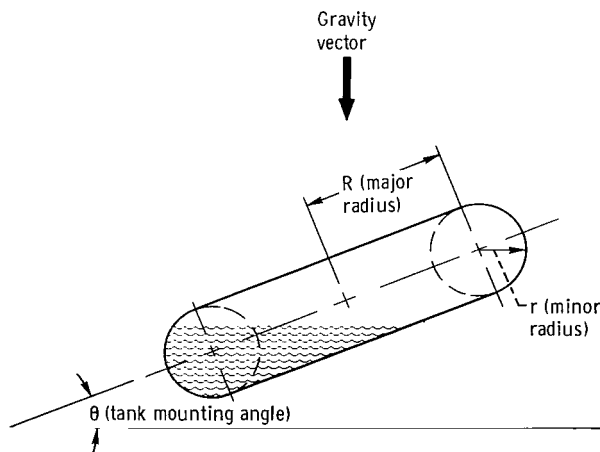


Figure 2. - Toroidal tank orientation.

Initial Condition  $\theta = 0^\circ$

At moderate to high percentages of liquid volume, the liquid moved to the tank wall furthest from the tank axis. The toroidal vapor cavity then separated to form one or more bubbles that were generally shaped as segments of a toroid with hemispherical

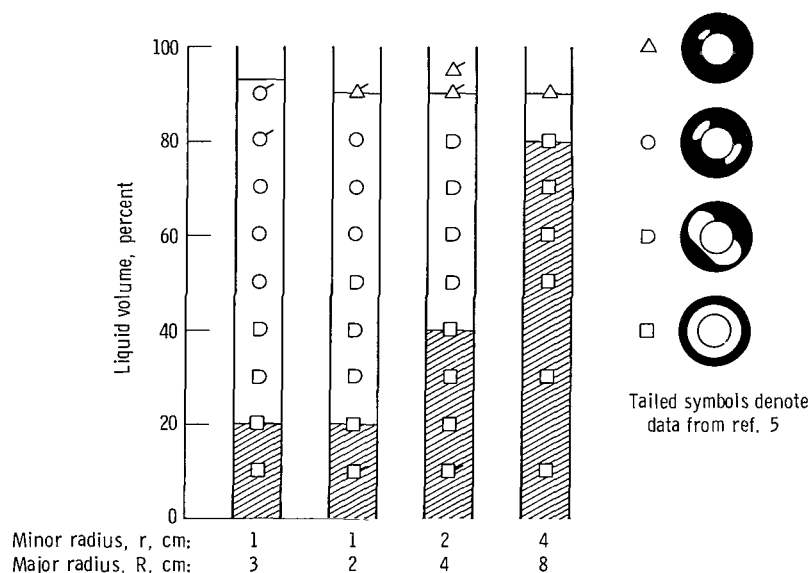
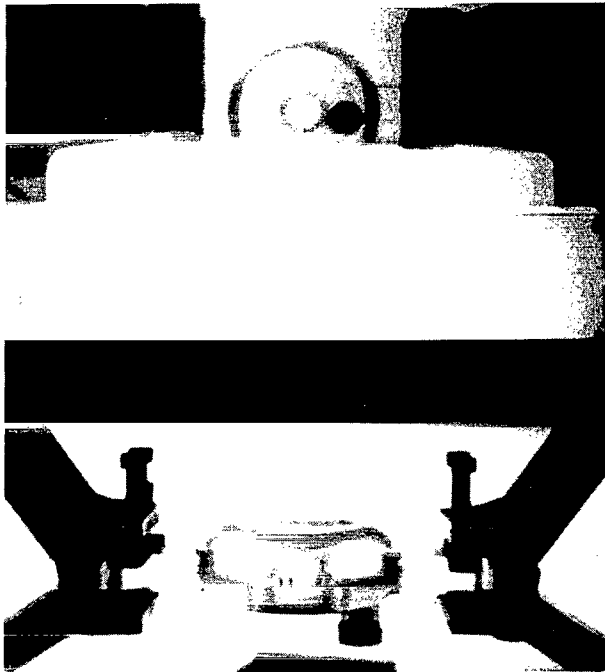
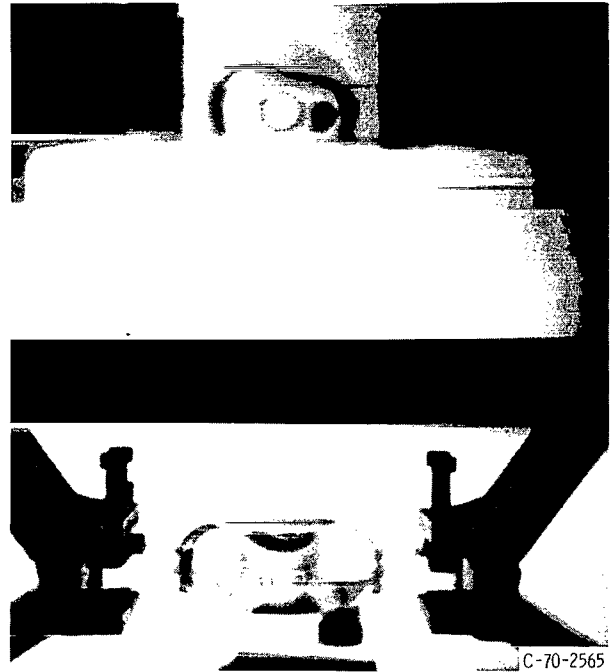


Figure 3. - Effect of percentage of liquid volume and tank geometry on liquid-vapor interface configuration during weightlessness. Tank mounting angle,  $\theta = 0^\circ$ .



(a) Normal-gravity configuration.



(b) Zero-gravity configuration.

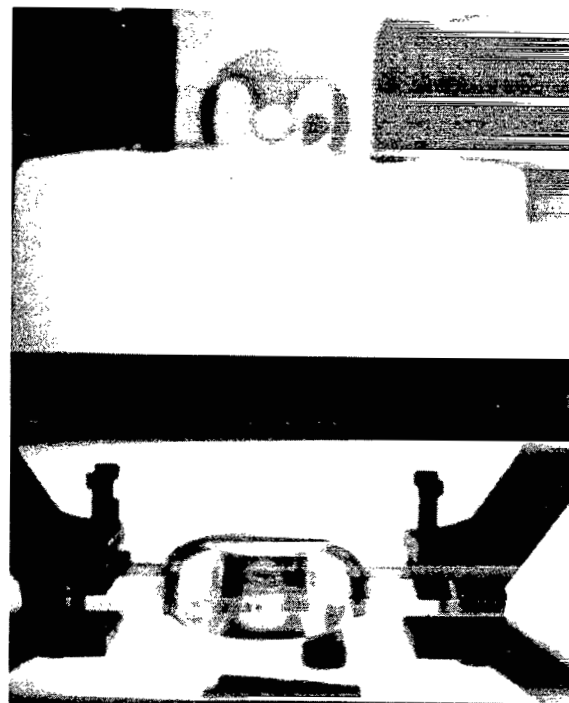
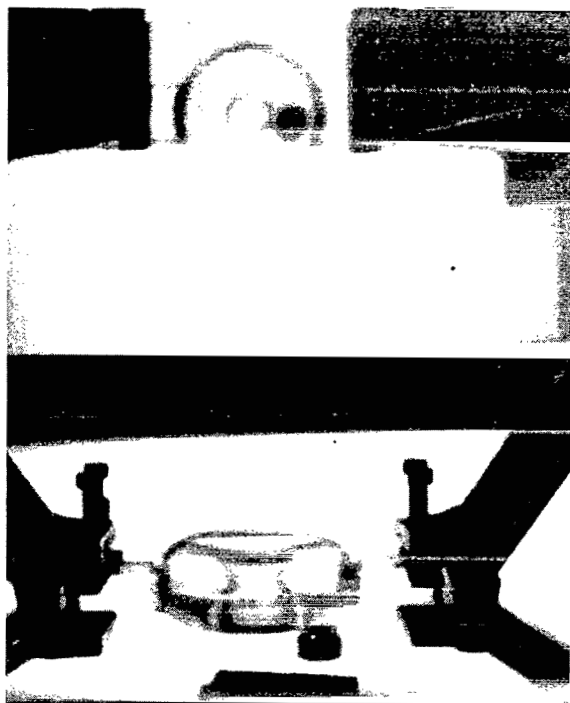
Figure 4. - Configuration of liquid-vapor interface during weightlessness for toroidal tank with low percentage of liquid volume (e.g. 20 percent full) and 0° tank mounting angle. Major radius, 2 centimeters; minor radius, 1 centimeter.

ends (see fig. 5). Generally, as the percentage of liquid volume increased, the tendency of the vapor to form more than one bubble also increased; however, three bubbles were the most observed in any of these tests. As the percentage of liquid volume was increased, the resulting vapor bubble became smaller until the hemispherical ends met to form a spherical bubble. It is possible to calculate the percentage of liquid volume for a given tank geometry which would give a volume of vapor capable of forming one spherical bubble. The upper lines in figure 3 were drawn at this percentage of liquid volume. A typical configuration in this region is shown in figure 6.

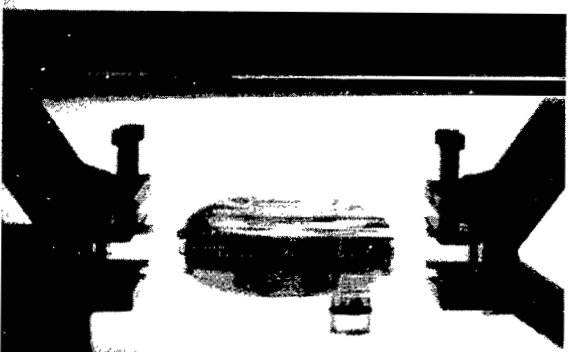
In conclusion, the equilibrium configuration of the liquid-vapor interface for tanks initially mounted at 0° is characterized over most of the range of percent liquid volumes by the formation of one or more vapor bubbles located randomly within the tank. These bubbles are generally shaped as segments of the toroid having hemispherical ends and tend to become spherical at high percentages of liquid volume. However, at low percentages of liquid volume, an essentially toroidal, stable vapor bubble is formed at the tank wall nearest the tank axis. The percent liquid volume limit below which this configuration existed was found to be about 20 percent, in contrast to the 50 percent limit reported in reference 5.

Normal-gravity configuration

Zero-gravity configuration



(a) 30 Percent full.

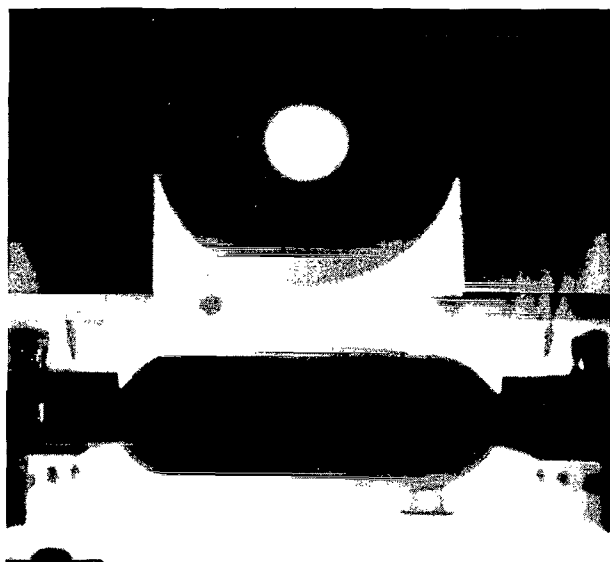


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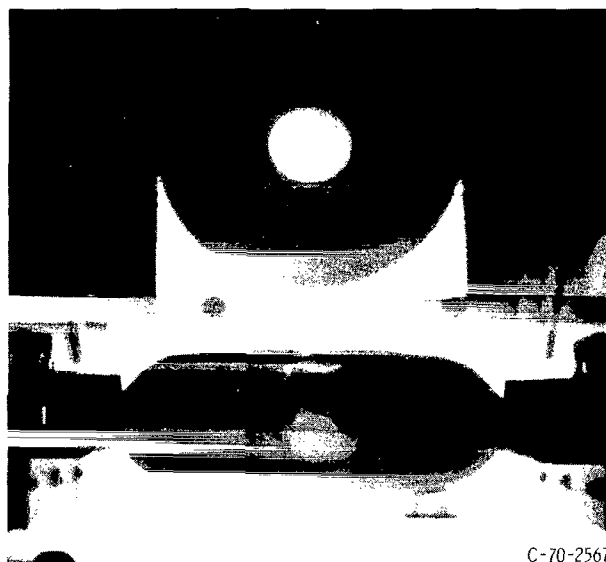
(b) 80 Percent full.

Figure 5. - Configuration of liquid-vapor interface during weightlessness for toroidal tank with moderate (30 percent full) to high (e.g. 80 percent full) percentage of liquid volume and 0° tank mounting angle. Major radius, 2 centimeters; minor radius, 1 centimeter.





(a) Normal-gravity configuration.



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(b) Zero-gravity configuration.

Figure 6. - Configuration of liquid-vapor interface during weightlessness for toroidal tank with high percentage of liquid volume (e.g. 90 percent) and  $0^\circ$  tank mounting angle. Major radius, 4 centimeters; minor radius, 2 centimeters.

### Initial condition $\theta > 0^\circ$

At tank mounting angles other than  $0^\circ$ , the liquid-vapor interface again formed two distinct configurations during weightlessness. The configurations were similar to those observed at a  $0^\circ$  tank mounting angle and were dependent on the percentage of liquid volume and the tank proportion. A composite graph, summarizing all the data (including that taken at  $\theta = 0^\circ$  and some from ref. 5), is presented in figure 7. The configurations indicated in figure 7(b) are for tanks having the same radius ratio (major radius/minor radius equal 2). It was assumed that they would thus have identical liquid-vapor interface configurations given ample test time.

At low percentages of liquid volume, the bulk of the liquid collects on the tank wall furthest from the tank axis and is primarily concentrated in that section of the tank in which it was initially located. This region is represented by the lower shaded portions of figure 7. Figure 8 presents typical configurations in this region. Note that the thickness of the liquid on the outer wall appears to be greatest at that location in the tank in which the normal-gravity depth was largest. This configuration is analogous to that formed at low percentages of liquid volume and tank mounting angles of  $0^\circ$ ; the only difference being that the liquid did not extend completely around the outer wall area. The lower shaded sections of figure 7 were drawn on the basis of this assumption.

At moderate to high percentages of liquid volume, the liquid completely filled one

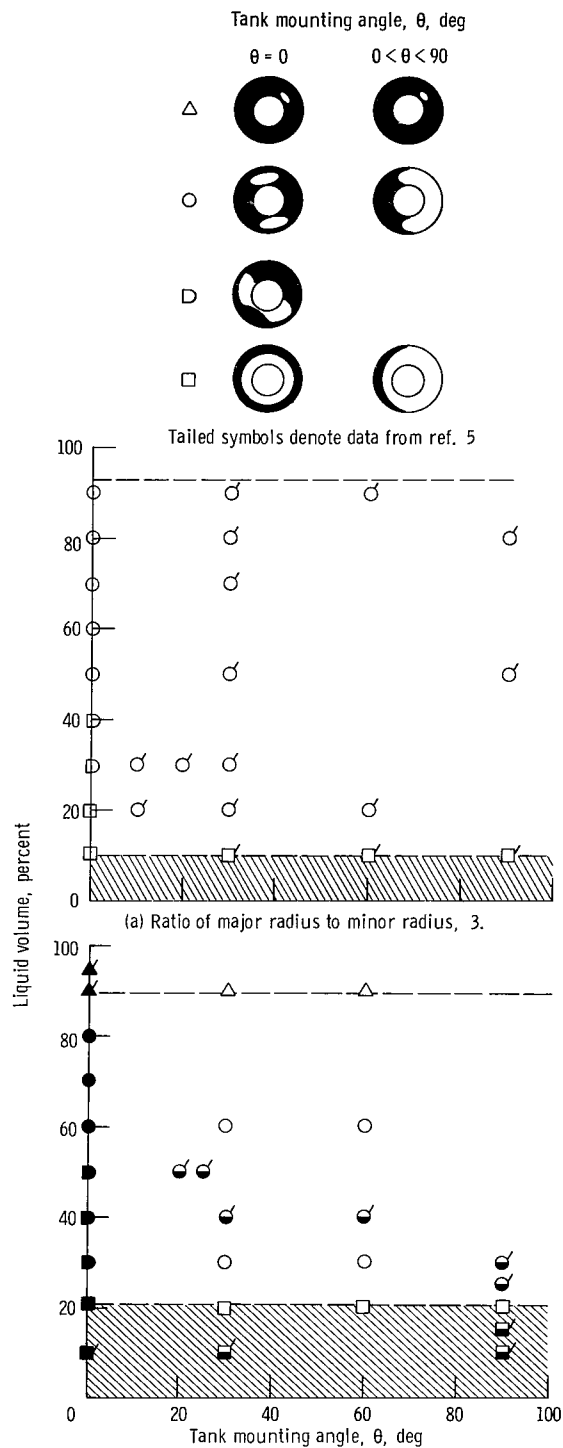
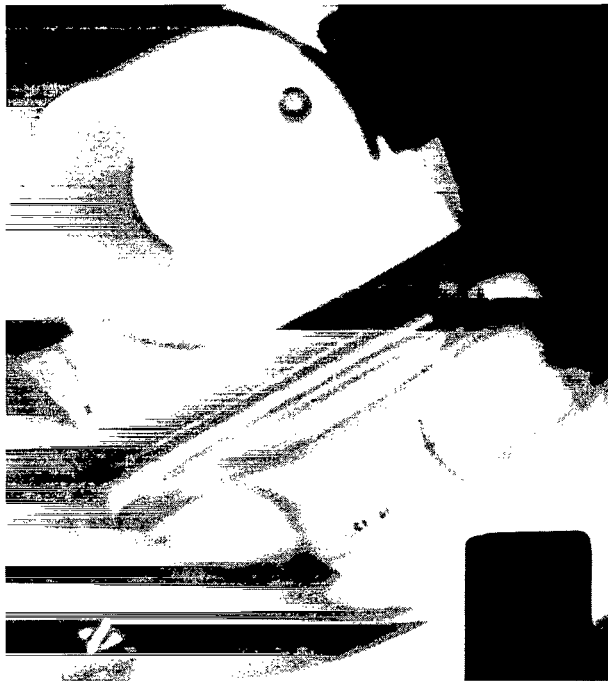


Figure 7. - Effect of percentage of liquid volume, tank mounting angle, and tank geometry on liquid-vapor interface during weightlessness.

Normal-gravity configuration

Zero-gravity configuration



(a) Tank mounting angle, 30°.



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(b) Tank mounting angle, 60°.

Figure 8. - Configuration of liquid-vapor interface during weightlessness for low percentage of liquid volume (e.g. 20 percent) and tank mounting angles greater than 0°. Major radius, 8 centimeters; minor radius, 4 centimeters.

Normal-gravity configuration

Zero-gravity configuration

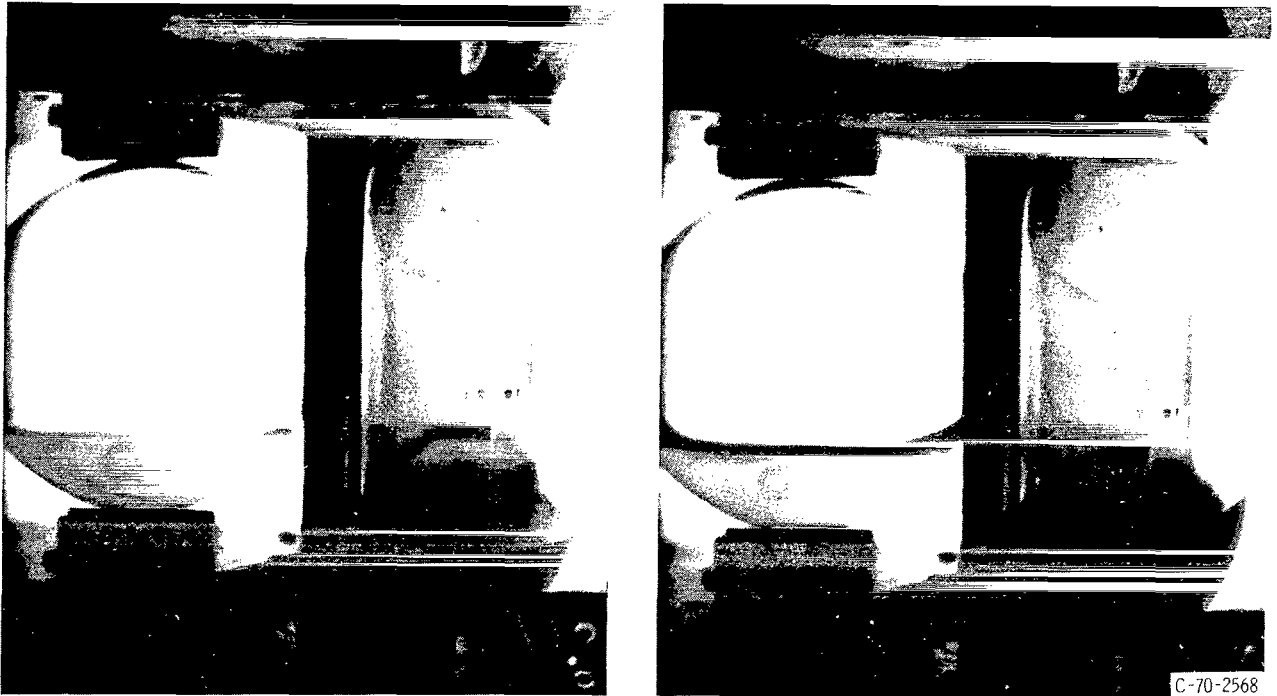
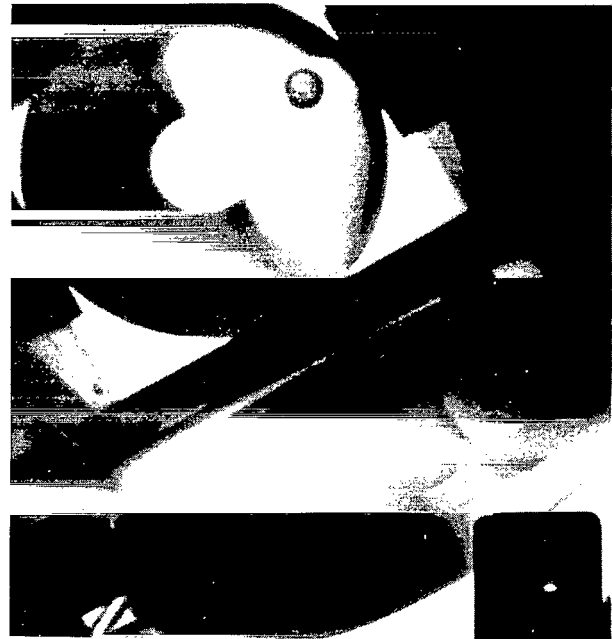
(c) Tank mounting angle,  $90^\circ$ .

Figure 8. - Concluded.

segment of the tank. This configuration is shown in figure 9. At either end of the filled segment, the liquid-vapor interface should have a constant curvature, with a radius approximately equal to the tank minor radius consistent with the liquid meeting the wall at a  $0^\circ$  contact angle. The configuration in this region is very similar to that which occurs over essentially the same range of percent liquid volume for tanks initially positioned at  $0^\circ$ . Note that for the tanks initially inclined at some angle, only one segment of the tank is filled while for the same tank mounted initially at  $0^\circ$ , two or more segments may be filled. As the percent liquid volume is increased, the hemispherical ends meet, resulting in a single spherical bubble (see fig. 10). The upper lines drawn in figure 7 represent this calculated percent liquid volume. Again, the liquid tends to remain in that section of the tank in which it was initially located.

Normal-gravity configuration

Zero-gravity configuration



(a) Tank mounting angle,  $30^\circ$ .

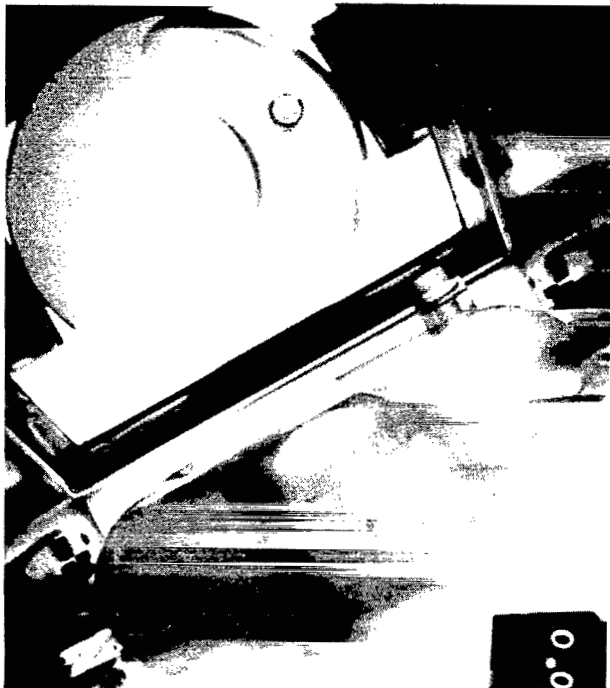


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(b) Tank mounting angle,  $60^\circ$ .

Figure 9. - Configuration of liquid-vapor interface during weightlessness for moderate to high percentage of liquid volume (e.g. 60 percent full) and tank mounting angles greater than  $0^\circ$ . Major radius, 8 centimeters; minor radius, 4 centimeters.

Normal-gravity configuration



Zero-gravity configuration



(a) Tank mounting angle,  $30^\circ$ .



(b) Tank mounting angle,  $60^\circ$ .

Figure 10. - Configuration of liquid-vapor interface during weightlessness for high percentage of liquid volume (e.g. 90 percent full) and for tank mounting angles greater than  $0^\circ$ . Major radius, 8 centimeters; minor radius, 4 centimeters.

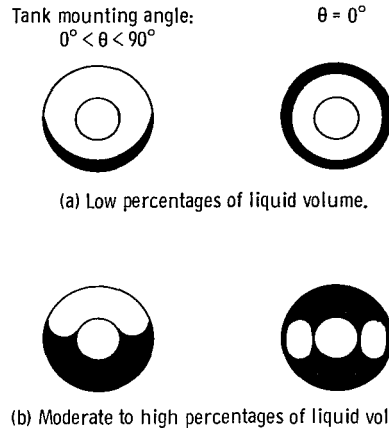


Figure 11. - Equilibrium liquid-vapor interface configurations in a toroidal tank. Static contact angle of liquid on tank material, near  $0^\circ$ .

## SUMMARY OF RESULTS

An experimental investigation was conducted to determine the final equilibrium configuration of a wetting liquid in a toroidal tank during weightlessness. The available weightless test time of about 5.1 seconds allowed a better definition of the final equilibrium configuration for the smaller tanks employed in reference 5 (particularly in the so-called transition region) and also permitted the study of a larger tank size. The results of the investigation are shown in figure 11 and summarized as follows:

1. At low percent liquid volumes (of the order of 20 percent depending on tank proportions) the liquid positioned itself on the wall furthest from the tank axis. For  $0^\circ$  tank mounting angle, the liquid extended completely around the outer wall; while for tank mounting angles other than  $0^\circ$ , only a portion of the outer wall was covered (see fig. 11(a)).
2. For moderate to high percent liquid volumes, the liquid completely filled one or more segments of the tank depending on tank inclination. At  $0^\circ$  tank mounting angle, no precise location of the resulting vapor bubbles could be predicted nor could any prediction be made concerning the number of bubbles formed (as many as three were observed). For tank mounting angles other than  $0^\circ$  (see fig. 11(b)), the liquid tended to remain in that section of the tank in which it was initially located and only a single vapor bubble was formed. Thus, the location of liquid and vapor was predictable.

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, July 31, 1970,  
124-08.

## APPENDIX - APPARATUS AND PROCEDURE

### Test Facility

The experiment data for this study were obtained in the Lewis Research Center's 5- to 10-Second Zero-Gravity Facility. A schematic diagram of this facility is shown in figure 12. The facility consists of a concrete-lined 8.5-meter (28-ft) diameter shaft that extends 155 meters (510 ft) below ground level. A steel vacuum chamber, 6.1 meters (20 ft) in diameter and 143 meters (470 ft) high, is contained within the concrete shaft. The pressure in this vacuum chamber is reduced to 13.3 newtons per square meter ( $1.3 \times 10^{-4}$  atm) by utilizing the Center's wind tunnel exhaust system and an exhaustor system located in the facility.

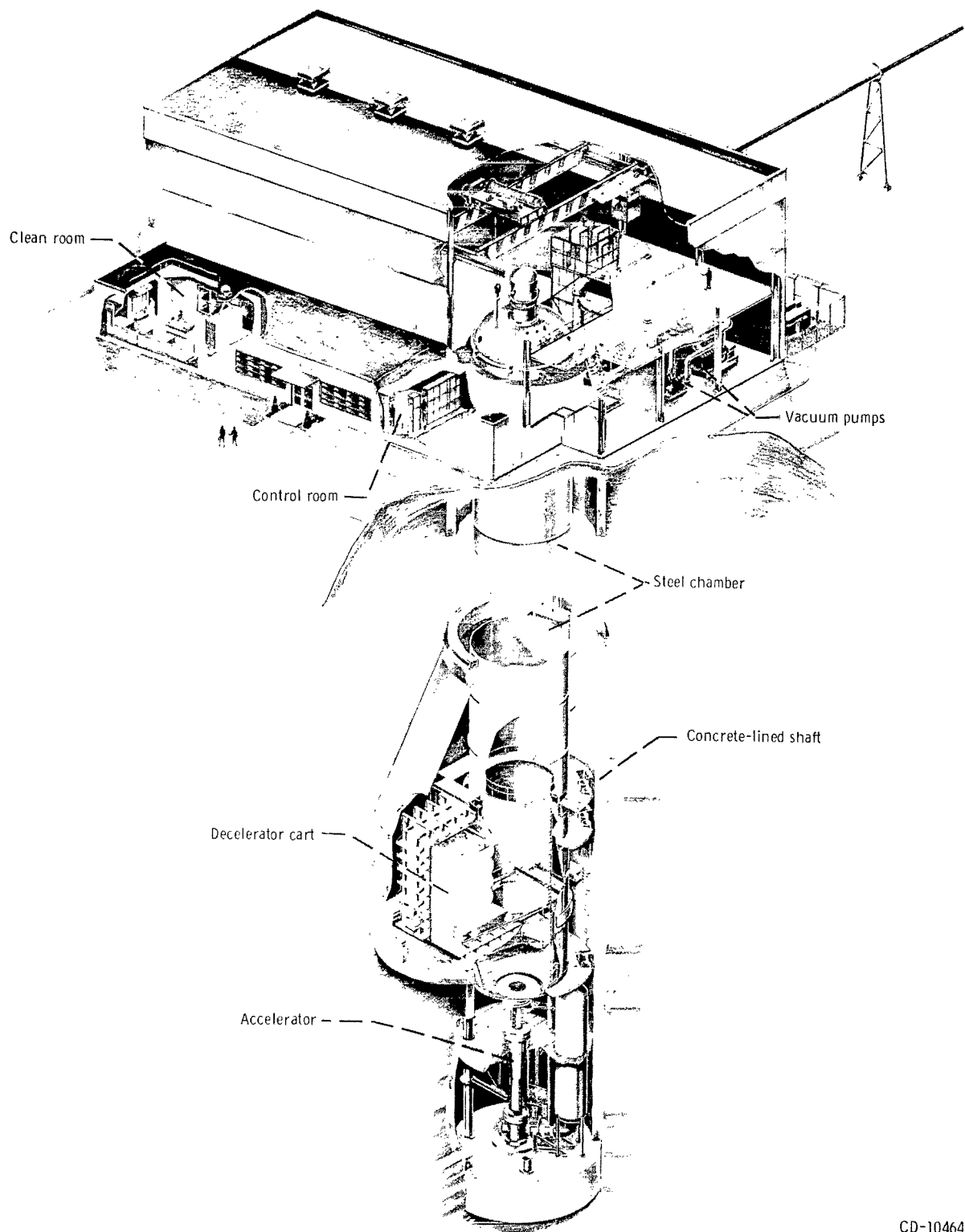
The ground-level service building has, as its major elements, a shop area, a control room, and a clean room. Assembly, servicing, and balancing of the experiment vehicle are accomplished in the shop area. Tests are conducted from the control room (see fig. 13), which contains the exhaustor control system, the experiment vehicle pre-drop checkout and control system, and the data retrieval system. Those components of the experiment which are in contact with the test fluid are prepared in the facility's class 10 000 clean room. The major elements of the clean room are an ultrasonic cleaning system (fig. 14(a)) and a class 100 laminar-flow work station (fig. 14(b)) for preparing those experiments requiring more than normal cleanliness.

Mode of operation. - The zero-gravity facility has two modes of operation. One is to allow the experiment vehicle to free-fall from the top of the vacuum chamber, which results in nominally 5 seconds of free-fall time. The second mode is to project the experiment vehicle upwards from the bottom of the vacuum chamber by a high-pressure pneumatic accelerator located on the vertical axis of the chamber. The total up-and-down trajectory of the experiment vehicle results in nominally 10 seconds of free-fall time. The 5-second mode of operation was used for this experimental study.

In either mode of operation, the experiment falls freely. That is, no guide wires, electrical lines, etc., are connected to the vehicle. Therefore, the only force (aside from gravity) acting on the freely falling experiment vehicle is due to residual air drag. This results in an equivalent gravitational acceleration acting on the experiment which is estimated to be of the order of  $10^{-5}$  g maximum.

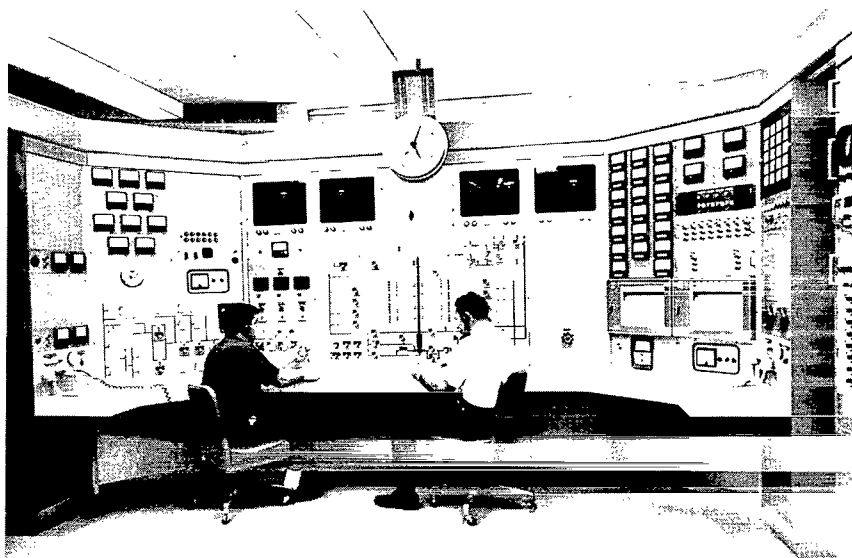
Recovery system. - After the experiment vehicle has traversed the total length of the vacuum chamber, it is decelerated in a 3.6-meter (12-ft) diameter, 6.1-meter (20-ft) deep container which is located on the vertical axis of the chamber and filled with small pellets of expanded polystyrene. The deceleration rate (averaging 32 g's) is controlled by the flow of pellets through the area between the experiment vehicle and the wall of the deceleration container. This deceleration container is mounted on a cart





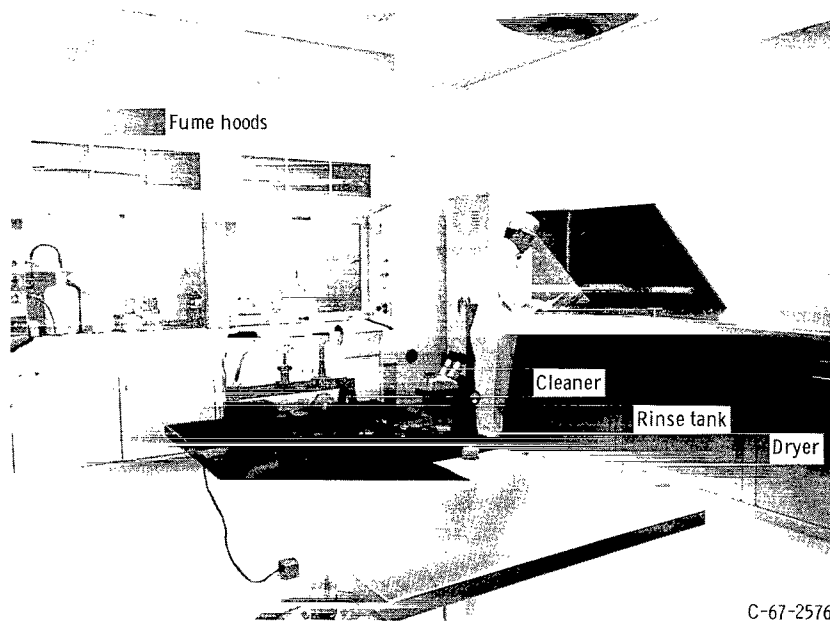
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Figure 12. - Schematic diagram of 5- to 10-Second Zero-Gravity Facility.

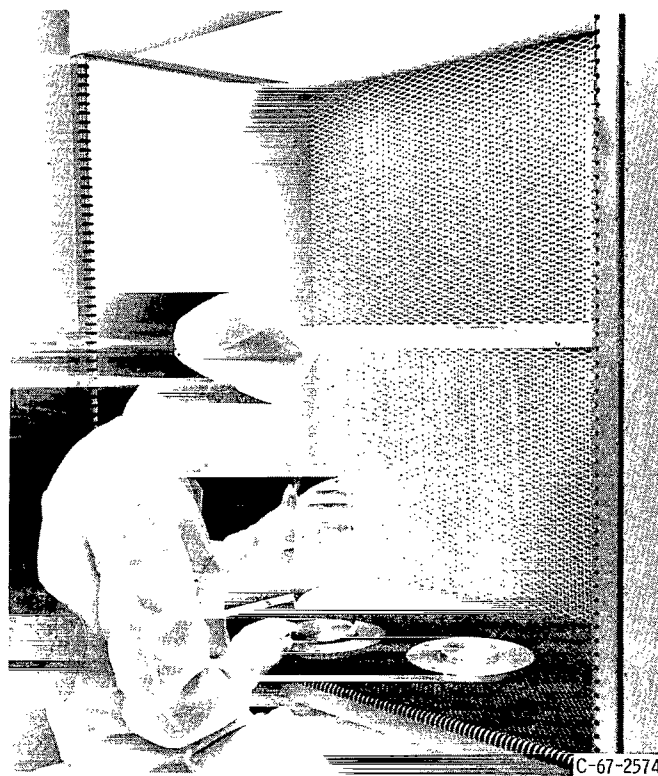


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Figure 13. - Control room.



(a) Ultrasonic cleaning system.



(b) Laminar-flow work station.

Figure 14. - Clean room.

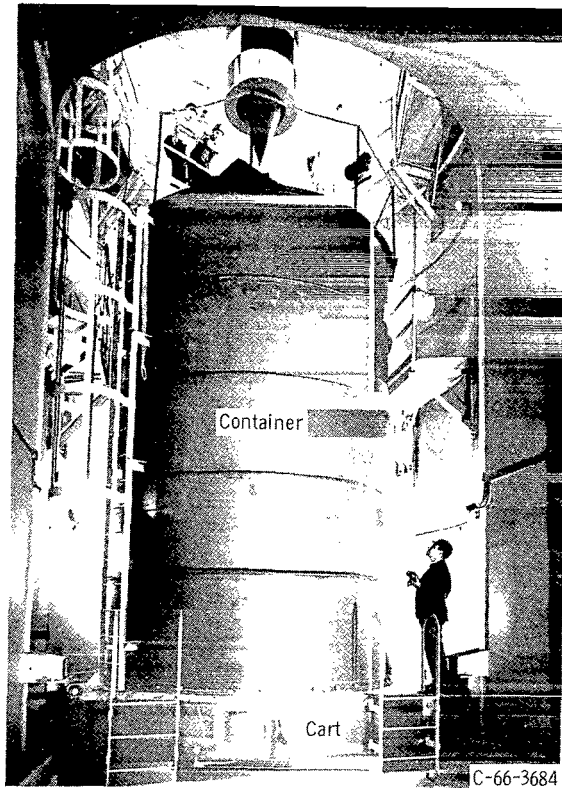


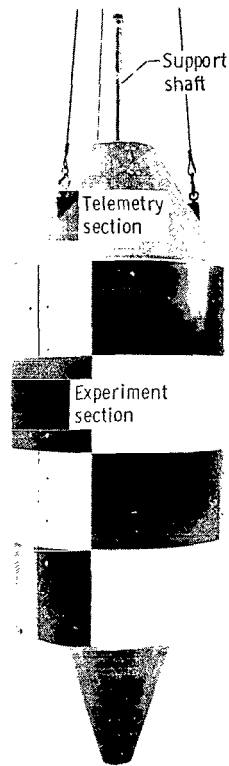
Figure 15. - Deceleration system.

which can be retracted prior to utilizing the 10-second mode of operation. In this mode of operation, the cart is deployed after the experiment vehicle is projected upward by the pneumatic accelerator. The deceleration container mounted on the cart is shown in figure 15.

## Experiment Vehicle

The experiment vehicle used to obtain the data for this study is shown in figure 16. The overall vehicle height (exclusive of the support shaft) is 3.0 meters (9.85 ft) and the largest diameter is 1.06 meters (3.5 ft). The vehicle consists of a telemetry system contained in the aft fairing and an experiment section which is housed in the cylindrical midsection.

Telemetry system. - The on-board telemetry system which is used to collect data is a standard Inter-Range Instrumentation Group (IRIG) FM/FM 2200-megahertz telemeter. It is used during a test drop to record as many as 18 channels of continuous data. The system frequency range extends to 2100 hertz. The telemetered data are



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Figure 16. - Experiment vehicle.

recorded on two high-response recording oscillographs located in the control room.

Experiment section. - The experiment section consists of the test tank, a photographic and lighting system, a digital clock, and an electrical system to operate the various components (see fig. 17). The test tank is indirectly illuminated by means of a backlighting system contained in the experiment housing which provides sufficient light so that the behavior of the liquid-vapor interface can be recorded by a high-speed, 16-millimeter camera. A mirror is positioned above the tank at a  $45^{\circ}$  angle to give a top view of the tank. A clock having a calibrated accuracy of  $\pm 0.01$  second is positioned within the field of view of the camera to give an indication of the elapsed time during the weightless drop. The electrical components onboard the package were operated through a control box and received their power from rechargeable nickel cadmium cells.

Test preparation. - The test preparation included ultrasonic cleaning, filling, and mounting of the tank in the experiment housing at the desired tank mounting angle.

The toroidal tank was cleaned in the ultrasonic cleaner with a mild aqueous detergent solution, rinsed with distilled water and dried in a warm-air dryer so that the wetting characteristics of the liquid would not be affected by contaminants. The tank

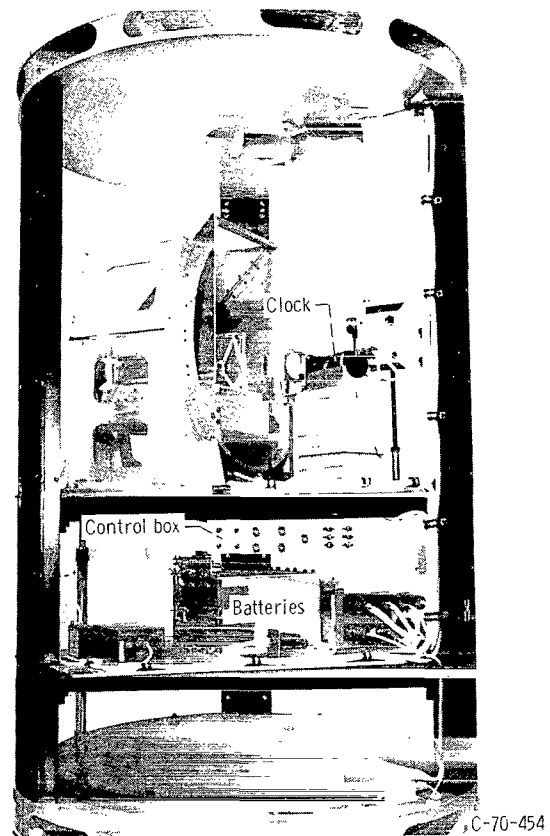
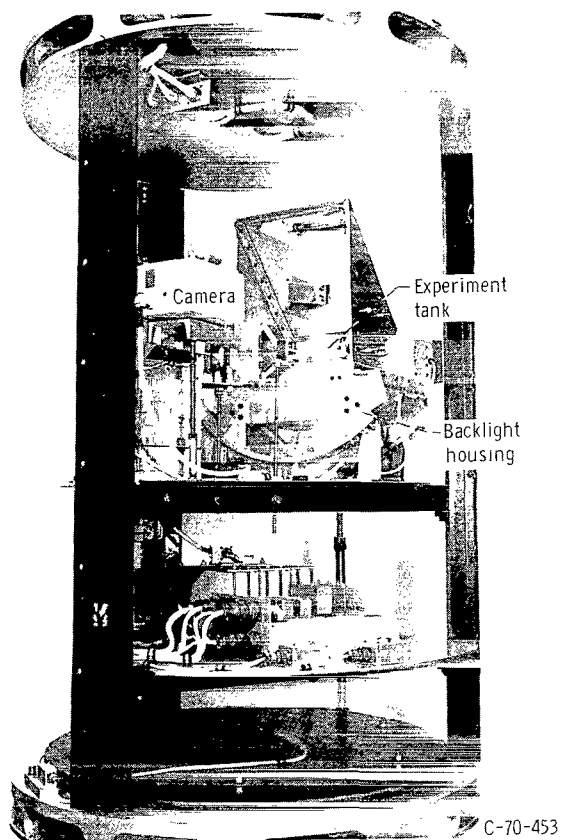


Figure 17. - Details of experiment package section.

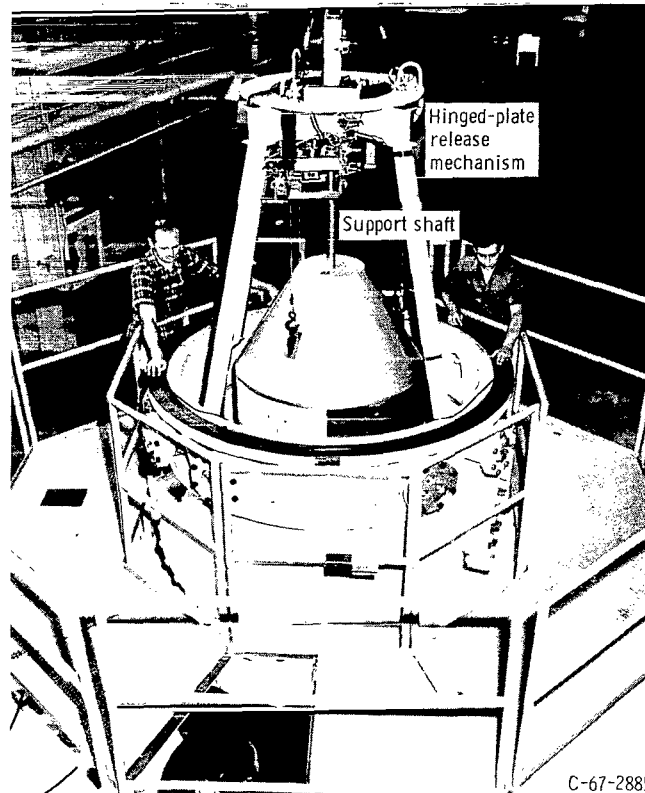


Figure 18. - Vehicle position prior to release.

was then filled with the required volume of test liquid in the clean room area and mounted in the experiment housing.

The tank mounting angle was then set by rotating the experiment backlighting housing about its semicircular base, and the entire experiment was balanced.

Test procedure. - The vehicle was then positioned at the top of the vacuum chamber, as shown in figure 18. It was suspended by the support shaft on a hinged-plate release mechanism. During vacuum chamber pumpdown and prior to release, monitoring of the experiment vehicle system was accomplished through an umbilical cable attached to the top of the support shaft. Electrical power was supplied from ground equipment. The system was switched to internal power a few minutes before release. The umbilical cable was remotely pulled from the shaft 0.5 second prior to release. The experiment vehicle was released by pneumatically shearing a bolt that was holding the hinged plate in the closed position. No measurable disturbances were imparted to the experiment by this release procedure.

The total free-fall test time obtained in this mode of operation is 5.16 seconds. During the test drop, the vehicle's trajectory and deceleration were monitored on closed-

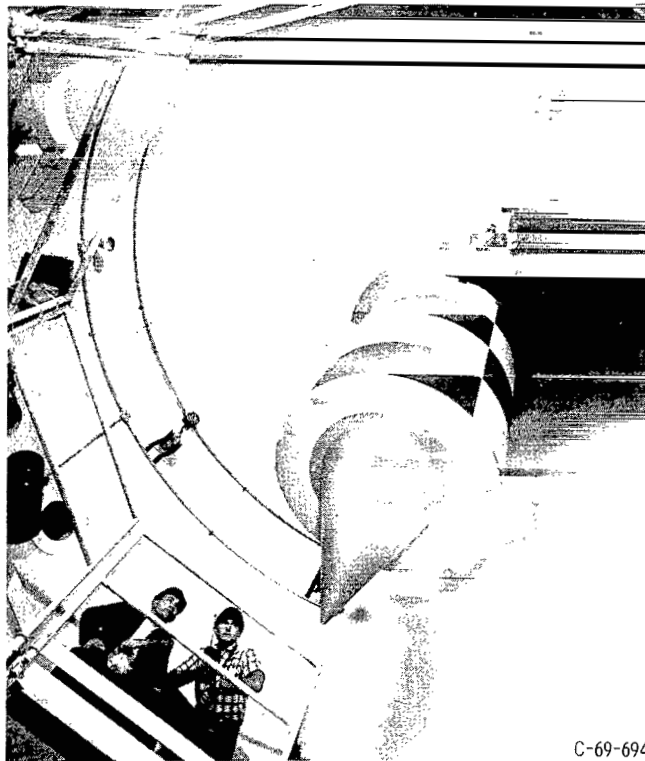


Figure 19. - Experiment vehicle being returned to ground level.

circuit television. Following the test drop, the vacuum chamber was vented to the atmosphere and the experiment returned to ground level (see fig. 19).



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